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EXPERIMENTAL EVALUATION OF ANTI-LOCK BRAKING SYSTEM PERFORMANCE ON ROUGH ROAD

N. VIVEKANANDAN[1] & Dr. AJAY M. FULAMBARKAR[2]

[1]*Scholar, Department of Mechanical Engineering, D Y Patil Institute of Technology & Assistant Professor, Pimpri Chinchwad College of Engineering, Pune, Maharashtra, India*

[2]*Principal, Department of Mechanical Engineering, Pimpri Chinchwad College of Engineering, Pune, India*

ABSTRACT

To prevent accidents, the vehicles have to be designed for stopping at shortest distance on braking without losing control. Still researchers are studying on advances in Anti-Lock Braking System (ABS) for different road conditions. From the investigation, it is found that the ABS performance on rough road surface decreases because of lack of predictability in road surfaces. The performance can be enhanced in rough road by controlling the suspension and using proper intelligent prediction algorithm. For this, Artificial Neural Network (ANN) is used to generate the road surface. ANN is useful for training the different road surfaces and trained data is used for faster response and reducing stopping distance. For simplicity purpose, a quarter car planar model was considered and results of simulation are validated with experimental results. An experimental test rig is developed for testing ABS on flat and rough road surface. The results obtained from experimental and theoretical are approximately same which shows intelligent algorithms are more beneficial.

KEYWORDS: Antilock Braking, Artificial Neural Network (ANN), Quarter Car, Rough Road Surface & Stopping Distance

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Original Article

1. INTRODUCTION

Now a days, Antilock Braking system is standard equipment in most cars. It is very difficult to model road and tyre interaction, hence the knowledge gained over the years by testing tyre -road interaction on different roads are being used to model the interaction. It is estimated that 20% of accidents are due to locking up of wheels. However, it is not possible to make simpler system to generalize situation for every road type like dry roads, wet roads, icy roads etc. Braking on slippery surfaces causes increase in stopping distance. Interestingly, poor road conditions are largest contributing environmental factor, responsible for fatal accidents. With an increase in off road Sport Utility Vehicle (SUVs), modeling rough road is an important area of research. Road input excited from rough terrain depreciates braking performance due to tyre contributing factors and deficiencies in ABS algorithm. Increased safety on off-road for the drivers and motorist those travel on road with poor surface condition is possible by solving the braking problem in rough road.

ABS shown in figure 1consist of –

i. Wheel speed sensors, ii. Electronic Controller Unit, iii. Hydraulic modulator Unitiv. Braking device

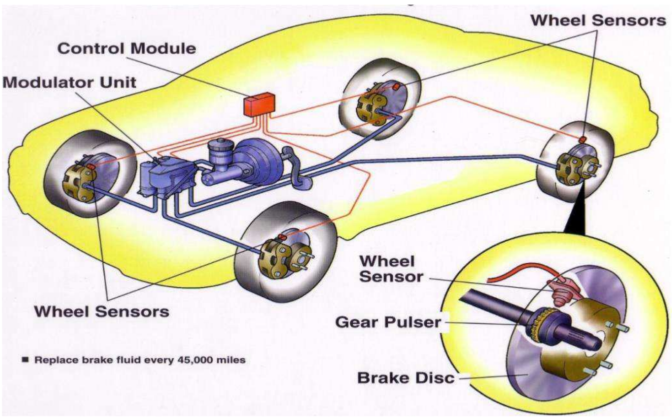


Figure 1: Overview of ABS Components [7].

2. WORKING OF ABS

ABS use hydraulic and systems combined to control the brakes without locking. During normal running, brakes are applied gradually but during the situation, if brakes are applied suddenly, the vehicle skids as wheels are locked.Wheel speed sensor is comprised of magnets, coils, toothed rotor and inductive pickup which translate the rotational speed of the wheel into sinusoidal waveform proportional to wheel speed in the form of pulses. The pulses are continuously provided to the E.C.U. The frequency of the pulses increases with the speed. As long as the frequency of the pulses from all wheels is about the same, then normal braking takes place. If pulses from the front wheel or rear wheel are slowing down rapidly, then it means that wheel speed is also slowing down too rapidly and the tire is beginning to skid. A serrated motor is affixed to the rotor, with a magnetic sensor situated crosswise to the serrated edge to find wheel rotation. The ABS actuator is hydraulic pressure unit that regulates the pressure to the brake lines according to the commands from the E.C.U. It is located downstream from the brake master cylinder. If a speed sensor indicates possible wheel lock, the E.C.U. orders the brake actuator to reduce hydraulic pressure. The system increases and decreases the pressure as necessary to bring near wheel-slip ratio to as near the ideal as possible.

3. LITERATURE REVIEW

Wietsche Clement et al. [1] calculated the decline of ABS performance on rough roads. ADAMS model used was not successful as expected for rough roads when simulation was compared with experimental. Herman A. Hamersma et al. [2] performed experimentation on the car equipped with semi active suspension on rough road. The simulation results highlighted by change in suspension characteristic best braking performance is obtained in rough roads. Valentin Ivanov et al. [3] developed control for cars with electric powertrain by controlling the wheel slip. A control strategy was developed for different tyre road contact. Theunis R. Botha et al. [4] generated the profile for the road to investigate vehicles performance in rough road condition. Rishabh Bhandari et al. [5] developed ABS with surface identification method by considering the deceleration effect and thereby preventing avoiding the wheel locking. Benjun Guo et al. [9] concluded that regular vehicles have limitations on rough roads due to more Degree of Freedom, issues with actuators and low level of performance. HakanKoylu et al. [10] studied the effect of vehicle dampers on rough roads and concluded that dampers have direct relationship with the brake pressure. ApichanKanjanavapastit et al. [11] investigated that the accidents can be avoided by knowing the profile of the road in advance. They used quarter car model to study the predict the profile of speed-bump.

4. ANALYTICAL STUDY

4.1 Vehicle Dynamic Model [8]

A simple quarter car model with required parameters is used for controller design. Figure 2 shows the model of the system. The degree of freedom is represented by vehicle's longitudinal velocity and wheel's rotational speed.

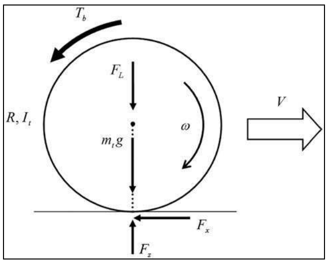


Figure 2: Free Body of Wheel During Braking [8].

The following equations are used to find various parameters required for the quarter car model.

$$\dot{V} = \frac{F_x}{m_t} \tag{1}$$

$$\dot{\omega} = \frac{RF_x}{I_t} \tag{2}$$

$$m_t = \frac{m_{vs}}{4} + m_w \tag{3}$$

$$F_z = m_t g - \frac{m_{vs} h_{cg}}{2l}\ddot{x} = m_t g - F_L \tag{4}$$

$$\lambda = \frac{(V - R\omega)}{V} \tag{5}$$

$$\dot{\lambda} = \frac{\dot{V}(1-\lambda) - R\dot{\omega}}{V} \tag{6}$$

$$F_x = \frac{C_i \lambda}{1-\lambda} f(S) \tag{7}$$

Where, $f(S) = \begin{cases} S(2-S) & if\ S < 1 \\ 1 & if\ S > 1 \end{cases}$

Table 1: Abbreviations

Symbol	Quantity	Symbol	Quantity
R	radius of wheel	h_{cg}	height of the sprung mass
I_t	total moment of inertia (wheel)	F_L	dynamic load transfer
V	vehicle's longitudinal velocity	C_i	tire longitudinal stiffness
ω	angular velocity of the wheel	C_α	cornering stiffness of the tire
T_b	braking torque	μ	road coefficient of friction
F_x	longitudinal tire force	λ	Slip
F_Z	normal load on tyre	ε_r	road adhesion reduction factor

Table 1 Contd.,			
m_t	total mass of the quarter vehicle	C_1	maximum value of the friction curve
m_{vs}	vehicle sprung mass	C_2	friction curve shape
m_w	wheel mass	C_3	difference between the maximum value of the friction curve and the value when slip ratio
l	wheel base		

4.2 Vehicle on Rough Road [1, 2]

Braking of the vehicles on rough roads is influenced by many factors such as axle oscillations, effect of suspensions, effect of tyre oscillation, sudden change in wheel speed etc. The main parameter longitudinal wheel slip is calculated using the wheel deceleration.

$$\%\,slip = \frac{V - R_{eff}\omega}{V} \times 100 \tag{8}$$

4.3 Intelligent Algorithm

Although this study includes intelligent algorithm, it is worth exploring the fundamentals as all modern ABS algorithm incorporates a certain amount of intelligence in order to adapt to the different terrains that the system might encounter. The intelligent algorithm is a modification of Bosch algorithm as shown in figure3. Two parameters are gradually adapted to optimize braking performance, namely the deceleration value R and the slip $\boldsymbol{\lambda}$. Intelligent algorithm consists of several parameters such as Neural network or fuzzy. Matlab having the inbuilt module of neural network tool box which is used for training the data to get a desired or target value.

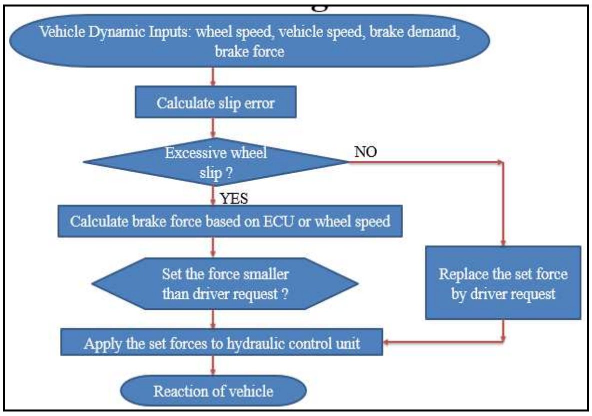


Figure 3: Flow Chart of Bosch Algorithm.

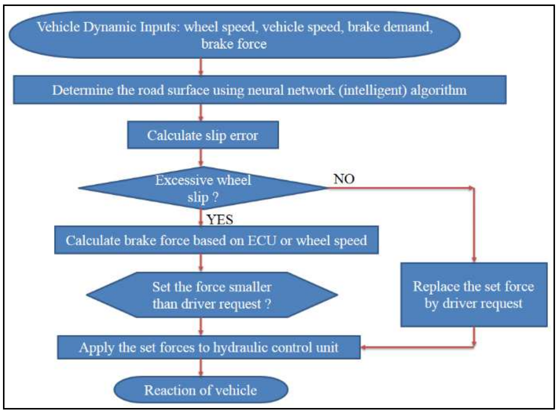


Figure 4: Flow Chart of Intelligent Algorithm.

This algorithm as shown in figure4 identifies the rough road surface using the pressure in suspension system during travelling on the rough terrain.

4.4 Surface Prediction [5]

For identifying the road surfaces, prediction algorithms are required.

4.4.1 Three-Point Prediction Method [5]

In this algorithm, the prediction of the surface features is done at 3 predefined slip ratios. Each surface is calculated by

$$\mu(\lambda) = \left(C_1\left(1 - e^{-C_2\lambda}\right)C_3\lambda\right). \tag{9}$$

Table 2: Values of Constant for Various Surfaces [5]

Surface Condition	C1	C2	C3
Dry rough	1.2801	23.99	0.52
Wet rough	0.857	33.822	0.347
Snow	0.1946	94.129	0.0646
Ice	0.05	306.39	0

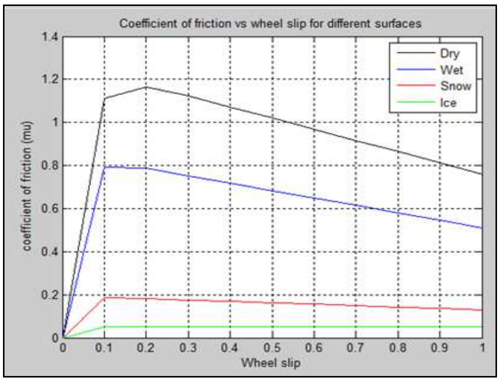


Figure 5: μ – λ Diagram for Different Surfaces.

Values from table 2 are implemented in a MATLAB program for different road surface and are plotted as in figure 6. It can be seen from figure 5 that μ is higher for all road condition at λ=0.1 and thereafterλ goes on decreasing. Hence major concern is at λ=0.1. According to the values of slip, we can determine the stopping distance and time required to stop vehicle.

4.5 Random Road Analysis[6]

For the generation of random road surface, Matlab Simulink model is considered according to ISO 8608 as shown in figure 6.

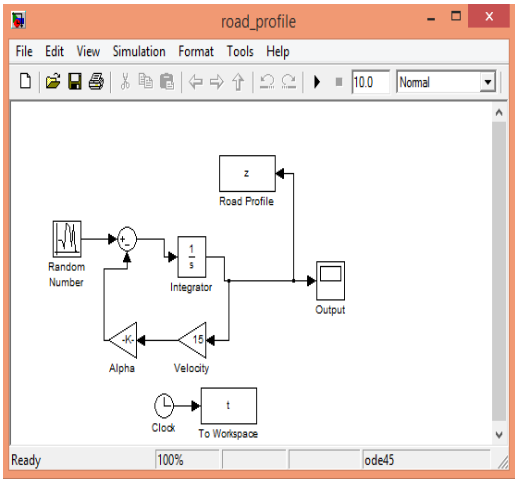


Figure 6: Random Road Generator Simulink Model.

Hence, for rough poor road surface (Class D) as per ISO 8608, the roughness variance is 20, mean is 2 and tyre of road surface α is 0.127. Velocity with which vehicle is moving is 15 m/s i.e. 54 km/hr.

4.6 Output of Rough Road Surface

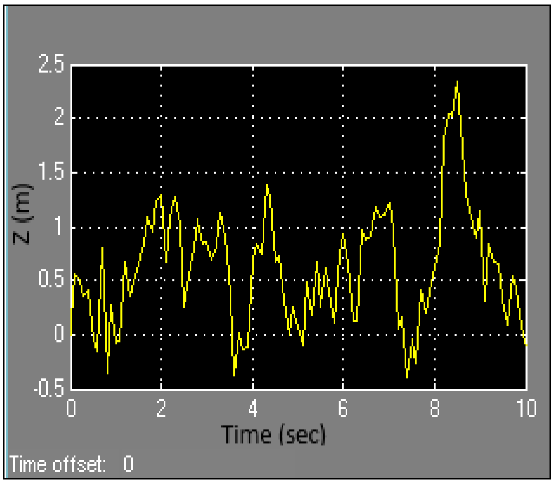
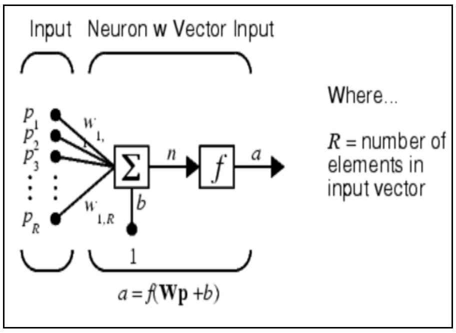


Figure 7: Generation of Road Profile.

Figure 7 gives the road profile generation. Figure shows some peaks due to variation of road. The amplitude values are store and are used in the Mathematical model developed in Simulink environment.

4.7 Intelligent Algorithm Using NeuralNetwork

Using ANN for the generation of rough road saves computational time, as it predicts the experimental result effectively. Multilayered Feed forward ANN is used for predicting the road condition as shown in figure 8.



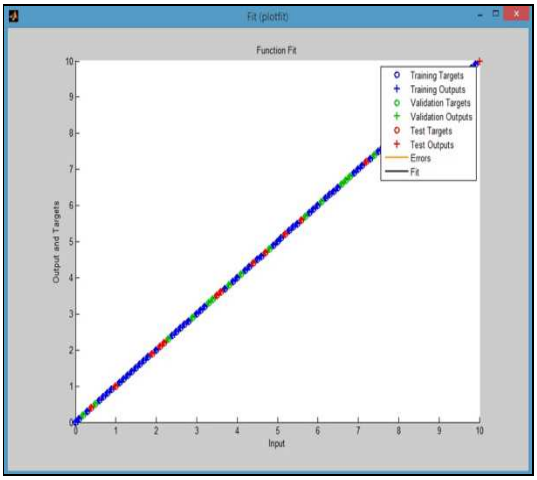
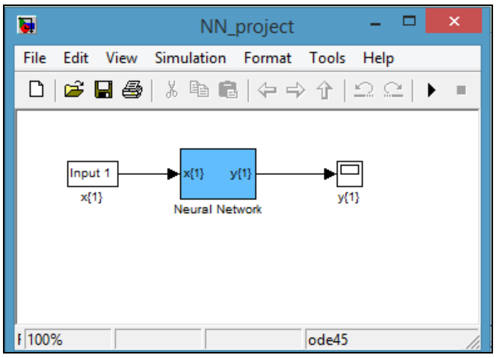


Figure 8: Multilayer Feed Forward Network **Figure 9: Plot Fit.**

Output obtained from figure 8 is considered for training data in neural network. Amplitude data and time data are considered in excel sheet and this data forms the input for neural network. The target is selected as we need a linear and stable surface of road. According to Levenberg Marquardt algorithm, 70% data are used for training and 15% for validation. As per the trial 20 hidden layer gave the better results with negligible error.

Figure 9 show the how good training is done. Blue color dots represent the training target while red color dots represent test target. Here, we can see that a smaller number of red dots, due to training limit is good.

4.8 Output of Artificial Neural Network



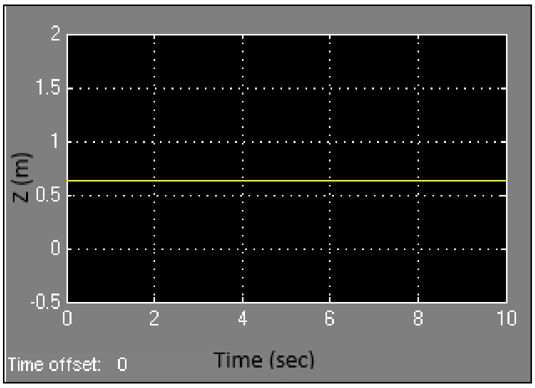


Figure 10: Output of Simulink Model of NN Figure 11: Output of Simulink Model of NN.

From training the input data to till such time we get the desired target output, which can be determined from plot fit diagram as shown in figure 10 and figure 11. Simulink model is generated from the neural network training toolbox. This Simulink model is helpful for implementation in ABS as trained rough road surface module.

4.9 ABS Simulink Model

ABS Simulink model is developed for a single wheel for hard braking condition as shown in figure 12. The slip will be 0, when the vehicle speed and wheel speed will be same. When the wheel is locked, it will be 1. A desirable slip value is set as 0.2. The output of neural network is road surface. An interface of wheel and road surface is done. As shown in figure 16, neural switch is used for interface. If the coefficient of friction is large, then road surface is selected to obtain linearity and stability of vehicle and vice versa. Output obtained from the Simulink model is more stable than without intelligent algorithm.

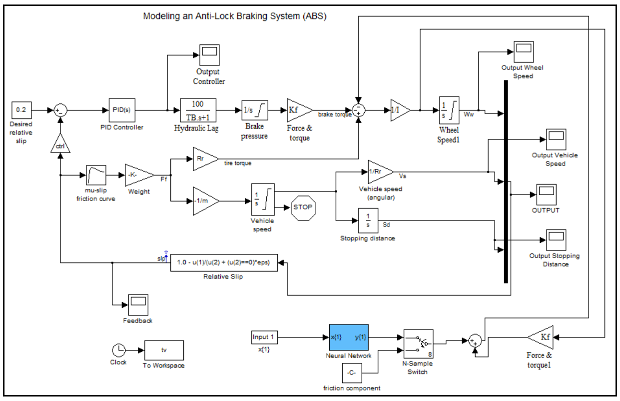
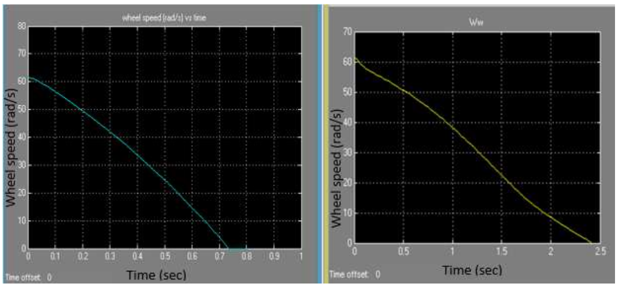


Figure 12: Simulink Model using Neural Network.

4.10 Output of Simulink Model

4.10.1 Wheel Speed

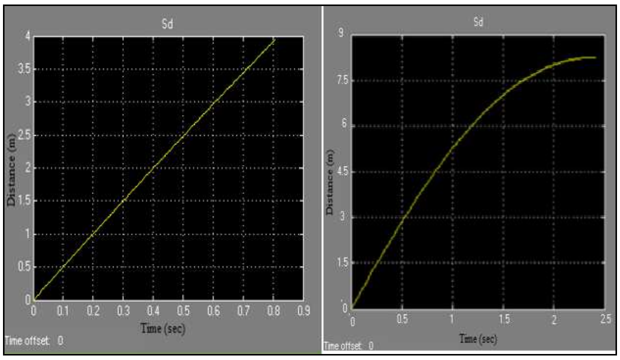
From figure 13 and figure 14, it is observed that the stopping time distance and distance increases respectively in rough road without intelligent algorithm because of irregularity in the road surface and the wheel looses its contact with road surface and has to cover long distance before stopping.



a) with Intelligent Algorithm b) without Intelligent Algorithm

Figure 13: Wheel Speed using a) with Intelligent algorithm b) without Intelligent Algorithm.

Figure 13 (a) and (b) shows the output of the Simulink model using neural network as an intelligent algorithm and without intelligent algorithm. From figure 13 it is clear that, time required with intelligent algorithm is less than without using intelligent algorithm by 68% and from figure 18, it is observed that the stopping distance is reduced by 51% for a vehicle speed of 15 km/hr (i.e.) 54 km/hr. The results indicate the significant benefit of utilizing intelligent algorithm.



a) with Intelligent Algorithm b) without Intelligent Algorithm

Figure 14: Stopping Distance using.

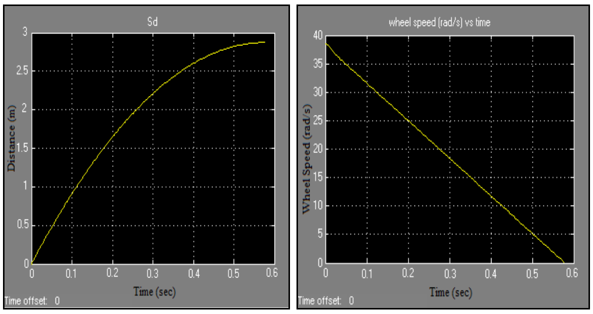
4.11 Results

Table 3: Result Table

Measurement Factor	Without Intelligent Algorithm	With Intelligent Algorithm	% Decrease
Stopping distance	8.22m	4m	51%
Settling Time	2.4 sec	0.8 sec	68%

4.11.1 Simulation Results at 10 m/s

Similar results were obtained at 10 m/s also. figure 15 shows the wheel speed and stopping distance at 10 m/s with intelligent algorithm.



a) with Intelligent Algorithm b) without Intelligent Algorithm

Figure 15: a) Wheel Speed vs Time b) Stopping Distance vs Time.

5. EXPERIMENTAL ANALYSIS

5.1 Experimental Setup

Experimental setup as shown in figure 16 is developed to validate the simulation work. Following figure shows the experimental setup. Two rolling wheels are provided. The lower wheel is considered as reference wheel for road surface. The upper wheel imitates the wheel of vehicle whereas lower wheel animates relative road motion. Lower wheel drives the upper wheel by friction contact.

The two different lower wheels are considered, one is for flat surface and another is for rough surface. The motor is connected to reference wheel to avoid damage to coupler on rough road surface. In this setup, Alto wheel is attached to the 2 HP motor by using coupler. To this motor dimmer is attached through which speed of wheel can be varied. RPM of DC motor can be varied up to 1500rpm.

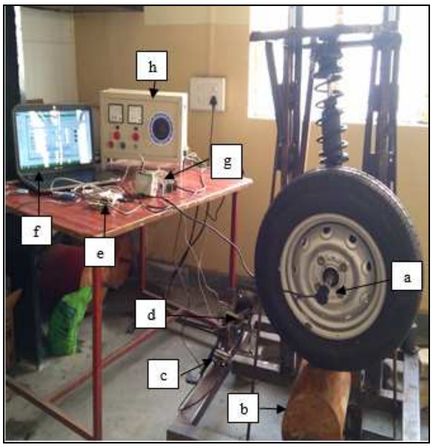


Figure 16: Experimental Setup a) Rotary Encoder b) Reference Wheel c) Load Cell d) Limit Switch e) DAQ f) LabVIEW front Panel g) PLC h) Dimmer Stat.

Table 4 indicates the list of materials used in experimental setup.

Table 4: Bill of Material

Sl. No.	Name	Quantity
1	Alto wheel assembly	1
2	Wooden wheel	1
3	DC Motor (2HP, 1800 rpm)	1
4	Linear Guideway	2
5	Flange Block	4
6	Dimmer	1
7	Rotary Incremental Encoder (10000 ppr)	1
8	Pad Load Cell (range of 0-50 kg)	1
9	Limit Switch	1

Wooden wheel is placed below alto wheel which gives us road condition to perform test. The motor speed is controlled with the help of dimmer stat. Motion of reference wheel is transferred to wheel which is connected to sprung mass with help of MacPherson strut. The two linear vertical guideways are used for up and down sliding motion. The speed of the wheel is measured by rotary encoders as shown in figure 17 and calculation of deceleration, slip and time required to stop the wheel after braking. Load cell is placed on the brake pedal as shown in figure18, shows the amount of brake force we have applied. To achieve more accuracy in calculation of distance travelled limit, switch is attached to the brake pedal.

When brake pedal is in contact with the limit, switch no pulses will be counted and when limit switch loses contact the brake pedal, then, it will start calculating pulses from which we can calculate stopping distance.

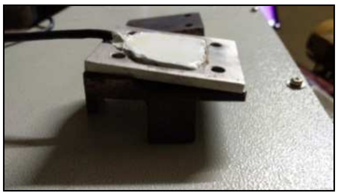




Figure 17: Rotary Encoder Attached to Car Wheel **Figure 18: Load Cell** **Figure 19: Load Cell in Casing.**

From this rotary encoder speed of vehicle wheel, deceleration of wheel and no. of rotations after the application brake are measured. The figure 19 shows the load cell and how it is assembled with the casing such that it won't get damaged as well as it will give us readings wherever we put our foot on brake pedal while braking. Load cell used is of pad type which can be easily mounted on brake pedal. This is of cantilever type so following type of arrangement is done.

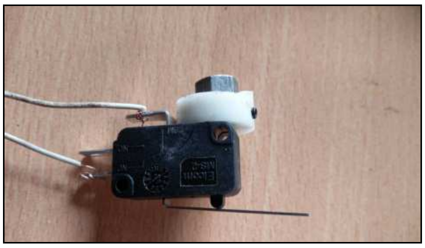
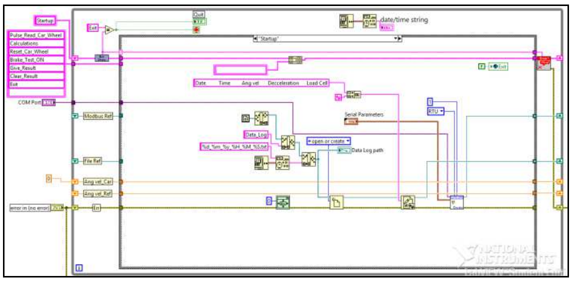



Figure 20: Limit Switch **Figure 21: Calculation Data Log Sheet.**

This type of load cell arrangement is directly placed on brake pedal. And brake is applied with foot. This arrangement is attached to NI module to measure the amount of load is applied at this load cell. NI module is used in DAQ for determining the actual values of load or force applied on the brake pedal as shown in Fig. 21. Load cell reads on current in mV which is converted into the newton and can be seen from front panel of LabVIEW.

There are three ports available on limit switch, they are as follow Ground, NO and NC. For this research purpose, Ground and NC are taken into consideration. Ground port of limit switch is attached to ground port of power supply, whereas NC port is attached to PLC. The figure 20 shows position of limit switch when there is no brake applied.

Purpose of addition of limit switch is such that when brake is applied no. of revolutions will be counted, to measure distance travelled after the application of brakes.

5.2 Calculations

To calculate parameters like stopping distance, time required for braking equations of motion have been taken into account. These parameters are calculated to validate the results of experiments.

5.2.1 Equations of Motion

$$s = u \times t + \times a \times t^2 \quad (15)$$

$$v2 = u^2 + 2 \times a \times s \quad (16)$$

$$v = u + a \times t \quad (17)$$

From these equations of motion, following equations are derived:

Deceleration of vehicle = $(-u^2/2s)$ (18)

where, u = Initial velocity, v = Final velocity, s = distance travelled, a = acceleration

Stopping distance (distance travelled), S = $(u^2/2\ \mu\ g)$ (19)

where, a = max. deceleration of vehicle

5.2.2 Force Required for Braking

Work done to bring vehicle to standstill is proportional to kinetic energy of vehicle.

work done to bring vehicle to standstill = F.S

where, F = average braking force, S = distance travelled

$F.S = m.v^2$ (20)

$F = (m.v^2/S)$ (21)

From above formulae stopping distance, brake force, time required to stop vehicle is calculated for 18km/hr (5 m/s) for different road surface as shown,

- **For flat road surface (μ = 0.8)**

Table 5: Result for Different Speed in Flat Road

Sl. No.	Speed (m/s)	Stopping Distance (m)	Stopping Time (sec)
1	5	1.108	0.4432
2	10	4.432	0.8864
3	15	9.972	1.3296
4	20	17.728	1.7728
5	25	27.7	2.216
6	30	39.888	2.6592
7	35	54.292	3.1024
8	40	70.912	3.5456

- **For rough road surface**

Bump is given to flat road surface as it moves in rotation call as rough road surface. The angle of inclination of bump is θ=20º and 30º. For this angle of inclination, following calculation are done.

Time (t) = (2 x V x Sinθ)/g (22)

Stopping Distance = (V x t)/2 (23)

For, = 30º

Table 6: Result for Different Speed In Flat Road in Rough Road

Velocity (m/s)	Time (sec.)	Stopping Distance (m)
5	0.509683996	1.27421
10	1.019367992	5.09684
15	1.529051988	11.46789
20	2.038735984	20.38736
25	2.54841998	31.85525
30	3.058103976	45.87156
35	3.567787971	62.43629
40	4.077471967	81.54944

5.2.3 Hydraulic Braking System

We have considered quarter car model and so force calculations are shown for single wheel. After the application of brake force at pedal is available at master cylinder. In this work, we have used brake system of Alto vehicle of Maruti Suzuki. Standard dimensions are given below which are considered to calculate braking force at different stages.

Master cylinder diameter (d_1) = 19 mm

Area of master cylinder =1134.1149 mm^2

Caliper diameter (d2) = 32 mm

Area of caliper = 3216.9908 mm^2

Pedal ratio =4:1

When 1kg of force i.e. 9.81N force is applied at brake pedal then brake force acting on master cylinder is 39.24 N. Force at caliper (clamping force) is calculated as, let F_1 be force acting on master cylinder and F_2 be clamping force, then

F_2 = 111.3068 N

Similarly, values of clamping force for brake pedal force up to 10 kg is shown in table 7.

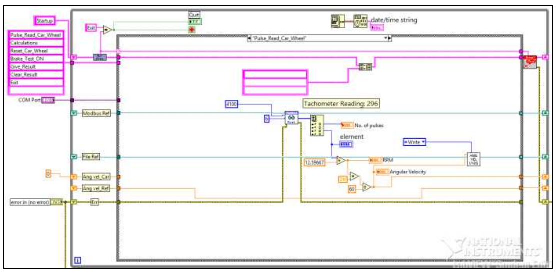
Table 7: Force at Different Positions

Sl. No	Force at Brake Pedal kg	Force at Master Cylinder, N	Force at Caliper, N
1	9.81	39.24	111.3068
2	19.62	78.48	222.6136
3	29.43	117.72	333.9204
4	39.24	156.96	445.2272
5	49.05	196.2	556.5341
6	58.86	235.44	667.8409
7	68.67	274.68	779.1477
8	78.48	313.92	890.4545
9	88.29	353.16	1001.761
10	98.1	392.4	1113.068

5.3 LabVIEW Program

LabVIEW is used to read the output given by rotary encoders and load cell. Two rotary incremental encoders are attached to the Programmable Logic Control (PLC). Through this, PLC pulses given by the encoders are measured and frequency of these pulses is measured to calculate revolutions per minute (rpm). Through this rpm, angular velocity and angular acceleration is calculated. Limit switch which is connected to brake pedal is also attached to the PLC. Load cell is attached to the NI 6009 module is placed to record readings. Output voltage of load cell is 10 mV, this module NI 6009 provides external excitation voltage to the load cell to read the readings. Slip ratio and wheel deceleration is calculated in LabVIEW. PID which was designed in MATLAB is also developed in same manner in LabVIEW.

The detailed block diagram of LabVIEW is shown in figure 22. It shows the data log sheet with date, time, angular velocity, deceleration and load cell values of force.Rotary encoder is connected through PLC which gives the number pulse reading. The angular velocity is calculated in RPM and Limit switch which is used to calculate the number of pulses reading after applying the brake.



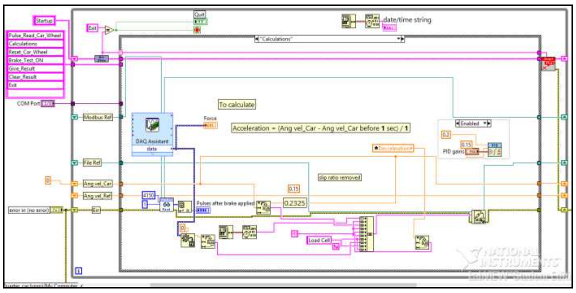


Figure 22: Calculations of Angular Velocity and Number of Pulse Reading Figure 23: Calculation of Acceleration and Force.

The figure 23 shows the calculation done for acceleration and other parameters like slip ratio and deceleration. The DAQ is used for load cell calculation which gives force applied on the brake pedal.

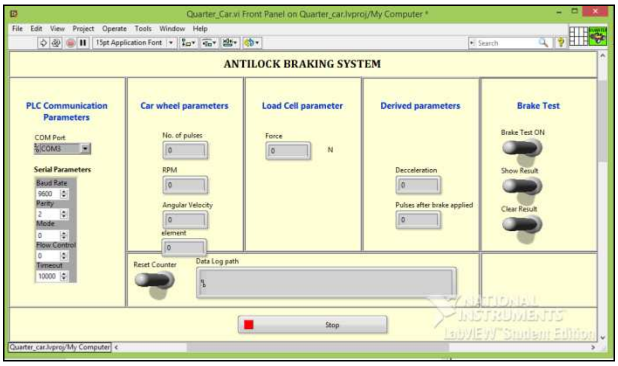


Figure 24: Virtual Interface for ABS.

As seen in above figure 24, column first gives us the parameters which are required to establish communication with the PLC. Second column named as the car wheel parameters gives us the output of rotary encoder attached to the Alto car wheel. First block of this column gives us the No. of pulses generated by rotary incremental encoder, second block gives us the RPM and third block gives us the angular velocity of encoder attached to the car wheel. The third column is for loading cell parameters which shows the force value in newton. Fourth column gives us the derived parameters which are the required output. This column gives us Slip ratio and wheel deceleration. Third block of this fourth column gives us the pulses after brakes applied as this block is connected to the limit switch. From this block, we can calculate stopping distance. Fifth column gives us the knobs which are required while performing brake test.

5.4 Results

Numerous experiments in real time were performed and results are compared with analytical results. To imitate the vehicle's behavior under braking on a rough road and flat road, the acceleration is provided to the wheel till the velocity of wheel reaches 5km/h to 35km/h and 55km/h. It should be noted that on the available setup experiments can be performed for specific road condition i.e. for dry conditions only.

Table 8: Result for flat road surface from Experimentation

Speed (m/s)	Stopping Distance (m)		Stooping Time (Sec)	
	Without Controller	With Controller	Without Controller	With Controller
10	4.432	2.5468	1	0.8864
15	9.972	5.786	2.5	1.3296

Table 9: Result for Rough Road Surface from Experimentation

Speed (m/s)	Stopping Distance (m)			Stopping Time (Sec)		
	Theoretical	Simulation	Experiment	Theoretical	Simulation	Experiment
10	5.09684	4.9	3.692	1.0193	1.58	2.3
15	11.46789	8.22	8.424	1.52905	2.8	3

It is observed from Table 8 that the stopping distance decreases by about 40% and the settling time also reduces by about 50%. The increase in the stopping distance and steeling time for performance of ABS on rough road is observed from Table 9. The stopping distance increases by about 44% and settling time also gets doubled for the system with ABS on rough road compared to system on flat road. However, the increase in performance parameter like stopping distance and steeling time is less compared to system without controller and the simulation results are closer to the experimental result thereby conforming the effective implementation of road profile generation done using Artificial Neural Network.

6. CONCLUSIONS

The Performance of ABS deteriorates in rough compared to performance of ABS in flat road. Hence, intelligent algorithm is used for identifying the road surface to have fast response of system. For training the algorithm using neural network, the coefficients of friction during wheel slip for rough is considered for surface roads. Trained output is given to Simulink model for generation of wheel speed stopping time and stopping distance. From the simulation and experimental results, it is clear that stopping distance and time are decreased for system with controller compared to system without controller both in flat and rough roads. From results, it is clear that theoretical and practical results are approximately equal and validated from the simulation results. Hence the intelligent algorithms are required to identify the road surface to get accuracy.

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AUTHOR'S PROFILE

N.Vivekanandan is currently working as the Assistant Professor in the department of Mechanical Engineering at Pimpri Chinchwad College of Engineering, Pune and is pursuing his Ph.D in Pune University. His area of interest includes Mechanical System Design, Vibration and Automotive safety. He completed his undergraduate degree in Mechanical Engineering in the year 1998 from Bharathiyar University, Coimbatore and, obtained his Post graduate degree in the year 2008 from National Institute of Technology (NIT), Trichy from the department of Mechanical Engineering with Industrial Safety Engineering as specialization. He is currently pursuing his Doctorate research in the area of Anti-lock Braking system (ABS). He has published papers in reputed National, International Conferences and Journals. He is a recipient of G.E. Foundation Scholar- Leader Program scholarship.

Dr.A.M.Fulambarkar is currently working as Principal, Pimpri Chinchwad College of Engineering, Pune. He carries academic and administrative experience of more than 30 years. He has been awarded Ph.D. in Mechanical Engineering by Nagpur University, Nagpur. He has published and presented research papers in various national and international conferences. He was chairman, Board of Studies of Mechanical Engineering in Nagpur University from 2000 to 2005. He is a Rotarian and associated with many Social Organizations.